Gold versus platinum thermocouples: performance data and an ITS-90 based reference function[a]

G. W. Burns, G. F. Strouse, B. M. Liu[b], and B. W. Mangum
National Institute of Standards and Technology
Gaithersburg, MD 20899

ABSTRACT

A reference function giving the thermoelectric voltage as a function of t_{90} over the range 0 °C to 1000 °C has been developed for the gold versus platinum (Au/Pt) thermocouple. Six Au/Pt thermocouples fabricated from 0.5 mm diameter wires of the highest purity (99.999+%) commercially available were compared with platinum resistance thermometers (PRTs) that were calibrated according to the ITS-90. Comparison measurements were made in stirred liquid baths in the range 0 °C to 550 °C and in a sodium heat pipe furnace from 545 °C up to 1000 °C. The thermoelectric voltages of the thermocouples were also determined at the freezing points of indium, tin, cadmium, zinc, aluminum, and silver. The repeatability of the thermocouples was established through repetitive measurements against PRTs and at the fixed points. The thermoelectric homogeneity of the thermocouples was assessed by determining their immersion characteristics in freezing-point cells. The stability of Au/Pt thermocouples with prolonged heating at the silver point (961.78 °C) and after rapid thermal cycling between the silver point and room temperature is reported also.

SUBJECT INDEX: Calibration methods, International Temperature Scale of 1990 (ITS-90), Noble metal thermocouple thermometers

INTRODUCTION

Work at the National Institute of Standards and Technology (NIST), formerly the National Bureau of Standards, on gold versus platinum (Au/Pt) thermocouples dates back to studies by Roeser and Wensel (1). In 1987, McLaren and Murdock published a report (2) on the characteristics of Au/Pt thermocouples that demonstrated the suitability for the use of such thermocouples at the 10 m°C level of imprecision at temperatures up to 1000 °C. Subsequent to that report, we undertook an investigation, beginning in 1988, of such thermocouples at NIST to determine their feasibility to serve as rugged secondary reference thermometers in industrial applications at the 50 m°C level of uncertainty. With the introduction of the International Temperature Scale of 1990 (ITS-90) (3), our emphasis shifted in 1990 to include the development of an ITS-90 based reference function for these thermocouples. Recently, a reference function for Au/Pt thermocouples, based on the ITS-90, was published by Gotoh *et al.* (4). In this paper, results of our investigations of the stability and reproducibility of these thermocouples and a reference function covering the range from 0 °C to 1000 °C are presented.

EXPERIMENTAL DETAILS

Thermocouple materials and preparation

Two different lots of 99.999+% purity of both platinum and gold wires (0.5 mm diameter) were purchased for this investigation from a commercial source. From these wires, thermocouples designated as 88-2, 88-3, 88-4 and 88-5 were prepared from the materials purchased in 1988, and thermocouples designated 89-12, 89-13 and 89-14 were prepared from materials purchased in 1989. The method of preparation of thermocouples 88-2, 88-3 and 89-12 followed the recommendations of Ref. 2. The platinum wires were annealed electrically in air at 1300 °C for 10 h, cooled rapidly (quenched) to room temperature and then heated for 1 h at about 450 °C. For annealing the gold wires, 63 cm long segments were mounted in a four-bore alumina insulating tube (1.2 mm bores, 4.7 mm in diameter, 76 cm long) that had been previously heated for 50 h at 1000 °C and then 5 h at 1100 °C. Then, this assembly was heated in a 1.1 m long horizontal-tube furnace for 10 h at 1000 °C, cooled over about 3.5 h to 450 °C, held at 450 °C for 20 h, and then removed from the furnace. The temperature over the central 82 cm long portion of the annealing furnace was uniform within ± 2 °C at both 450 °C and 1000 °C. Then, two of the Au wire segments were welded together and pulled into the bore of another alumina insulating tube (with the same dimensions and thermal treatment as that described above) with a Au pull-wire. An annealed platinum wire was pulled into another bore using a Pt pull-wire. The assembled thermocouples, 88-2, 88-3 and 89-12, were heated in the annealing furnace for 20 h at 450 °C.

The other four thermocouples (88-4, 88-5, 89-13 and 89-14) were prepared at a later time specifically for developing a reference function. Their preparation involved the same technique as that described above except that they were mounted in twin-bore alumina insulating tubes (1.6 mm bores, 4.7 mm in diameter and 76 cm long) and then given a furnace anneal at 1000 °C for 1 h, cooled over about 3.5 h to 450 °C, held at 450 °C for 20 h, and then cooled very slowly in the furnace to near room temperature.

The wires emerging from the alumina insulating tubes were insulated with flexible fiber-glass tubing to within about 2 cm of their ends. The fiber-glass tubing was then joined to the alumina tubes with heat-shrinkable tubing. To complete the assembly of the thermocouples, a pair of polyvinyl-insulated Cu wires (0.4 mm in diameter) was soldered to the Au and Pt wires to form the reference junctions. These Cu wire pairs were specially selected to be thermoelectrically identical within 0.02 μV when measured at room temperature relative to an ice bath.

Except for 88-3, a 4- or 5-turn coil, 1 mm in diameter, of 0.12 mm Pt wire connected the Au and Pt thermocouple wires at the measuring junction. The Au/Pt thermocouple assemblies were provided with small bar-type clamps installed to softly compress the insulation against the thermocouple wires. The use of a Pt stress-relieving coil to account for the differential thermal expansion of the Au and Pt wires and a bar-type clamp to anchor the wires at the room-temperature end of the alumina insulating tube also follows the recommendations of Ref. 2.

Throughout the experiment, the thermocouples received overnight furnace anneals at 450 °C after cooling them to room temperature following measurements in Al and Ag fixed-point cells.

Experimental procedures and apparatus

Initial measurements of thermocouple stability were conducted using the equipment described in detail in NIST Special Publication 250-35 (5). Measurements of long-term stability, involving rapid thermal cycling, were made using thermocouple 88-3. The results reported here for that thermocouple were obtained at the Ag freezing-point temperature, using cell Ag-65-2. The thermometer well in the cell contained a thermocouple protecting tube (6 mm i.d., 8 mm o.d.) made of fused silica glass and closed at one end. The outer surface of the tube was roughened to lessen heat losses by radiation piping up the walls of the tubing. After initiating a freeze in the silver cell, 88-3 was inserted into the cell over a time of 30 s and its measuring junction was positioned approximately 2 cm below the surface of the silver. The thermocouple was held at this location for 15 to 20 minutes and then its *emf* was recorded. The immersion of 88-3 was then increased by 1 cm and after 2 min its *emf* was again recorded. This procedure was repeated until 88-3 was fully immersed (approximately 14 cm) in the freezing-point cell. After it was held at full immersion for 12 min, its *emf* was measured. It was then withdrawn from the cell at the rate of 1 cm/2 min and its *emf* was measured while its measuring junction was held at each of the immersion locations used during insertion. After the measurement at the 2 cm immersion position was completed, 88-3 was removed rapidly (≤5 s) from the cell and cooled to room temperature. Thermocouple 88-3 was heated in the silver freezing-point cell for 1000 h at temperatures between 961 °C and 965 °C. During this period of time, it was cooled rapidly to room temperature 112 times and its *emf* was determined during 38 silver freezes.

Apart from these initial measurements of stability, all other measurements involving reproducibility and those for determining the reference function were made using constant-temperature liquid baths and the furnaces and fixed-point cells involved in the calibration (6, 7) of standard platinum resistance thermometers (SPRTs) and high-temperature standard platinum resistance thermometers (HTSPRTs). The latter measurements were made on thermocouples 88-2, 88-4, 88-5, 89-12, 89-13 and 89-14. Thermocouples 88-2 and 89-12 had experienced more than 600 h at temperatures in the range 420 °C to 965 °C prior to the measurements described below.

The comparison measurements between the thermocouples and the platinum resistance thermometers (PRTs) were made in stirred-liquid baths from 10 °C up to 550 °C and in a sodium heat-pipe furnace with an Inconel-block comparator from 545 °C up to 1000 °C. The comparator had a cylindrical Inconel block, 25 cm long and 4.9 cm in diameter, with 6 wells for thermocouples equally spaced on a 3.1 cm diameter circle and a central, axial well for the HTSPRT. Each of the thermocouple wells contained an alumina protecting tube (5 mm i.d., 6.5 mm o.d.). The HTSPRT was protected from contamination from metal ions by inserting it into a platinum test tube (56 cm long, with a wall thickness of 0.13 mm) that was located between two 56 cm long fused-silica test tubes (7). The automatic data acquisition system, other measuring instruments and constant-temperature control systems used in this experiment were the same as those described in Ref. 8. The thermometers used in this investigation[c] were an SPRT (25.5 Ω Chino model R800-2) and the two HTSPRTs (0.59 Ω VNIIM, designated HTSPRT I and HTSPRT J of Ref. 9), calibrated (7) on the ITS-90. The interpolation method used for determining temperatures with the HTSPRTs above the freezing point of silver is discussed in Ref. 9. The 25.5 Ω SPRT was used for measurements over the range from 0 °C to 550 °C. After each measurement sequence, the SPRT was also measured at the triple point of water (TPW). The equivalent temperature change at the TPW during the comparison measurements was about 0.6 m°C. The difference between the calibrations of the SPRT performed before and after the comparison measurements was not more than 0.5 m°C. The HTSPRTs were calibrated (see calibrations of HTSPRTs I and J in Ref. 9) before and after each of the comparison runs in which they were used.

The first measurement sequence for the thermocouples over the range 0 °C to 1000 °C was: 1) water bath (10 °C to 95 °C); 2) oil bath (95 °C to 180 °C); 3) ice bath (0 °C); 4) freezing points of In, Sn, Cd and Zn; 5) salt bath (275 °C to 550 °C); 6) freezing points of Al; 7) overnight furnace anneal at 450 °C (OFA); 8) freezing point of Ag, 9) OFA; 10) sodium heat-pipe furnace with Inconel-block comparator (545 °C to 1000 °C); 11) freezing point of Ag; 12) OFA; 13) freezing point of Al; 14) OFA; and 15) freezing points of Zn, Cd, Sn and In. During this first measurement sequence, the comparison measurements with thermocouple 88-4 were randomly repeated on different days in each of the constant-temperature liquid baths to obtain information on reproducibility. During the comparison measurements in the liquid baths and in the Inconel-block comparator, the thermocouples were positioned such that their measuring junctions were located at the same immersion as the midpoint of the sensing element of the PRT.

The reference junctions of the thermocouples were maintained at 0 °C in an ice bath when measurements were made. The junctions between the thermocouple wires and the copper wires were contained in closed-end glass tubes (6 mm o.d., 4 mm i.d.), and they were immersed 22 cm in the ice bath.

For the initial run in the Inconel-block comparator, the maximum allowable rate of change in the comparator temperature, when comparison measurements were made, was set at 2 m°C/min. This rate enabled the measurements from 545 °C up to 1000 °C to be completed within four days, but it resulted in unacceptable temperature uniformity within the comparator block. Although the thermocouple data from this run agreed to within the equivalent of 10 m°C with the salt bath and the Al freezing-point data, and to within 20 m°C with the Ag freezing-point data, the *emf* values were systematically higher than those measured in the salt bath and in the fixed-point cells. Three additional runs were made with the six thermocouples in the Inconel-block comparator in which the allowable rate of temperature change was reduced to ≤ 1 m°C/min. In the second run, the comparator data were in better agreement with the salt bath and Al-point data, but showed no improvement at the Ag point. Consequently, prior to the third run, a 4-cm long Inconel guard block was inserted above the comparator block, separated from the block with about 2 cm of insulation. The results from the third run were virtually the same as those of the second run. To improve the situation at the high temperatures, a series of nine Inconel radiation shields, spaced 1 cm apart, was inserted above the guard block. Additionally, the comparator block and its assembly were inserted about 3 cm deeper into the heat pipe. Following these changes, the results from the fourth run showed excellent agreement with the Ag-point data.

HTSPRT I was used in the first and fourth runs in the Inconel-block comparator; HTSPRT J was used in the second and third runs. Following each run, measurements of the thermocouples in each of the fixed-point cells were made. Also, prior to the fourth run, thermocouples 88-4, 88-5, 89-13, and 89-14 were given a 1-h furnace anneal at 970 °C, followed by 20 h at 450 °C. Then they were measured again in all of the fixed-point cells. This set of fixed-point measurements and those after the second and third runs were taken in descending order, Ag to In. The set after the fourth run was taken in ascending order.

RESULTS AND DISCUSSION

The stability results on thermocouple 88-3 were obtained over a period of two years. The thermocouple was heated in the silver freezing-point cell for a total of 1000 h at temperatures between 961 °C and 965 °C. During this period of time, it was cooled rapidly to room temperature 112 times and its *emf* was determined during insertions into, and withdrawals from, the Ag freezing-point cell during 38 silver freezes. During the first 25 silver freezes (415 h),. 88-3 had a conventionally welded measuring junction (no Pt coil or bar clamp). The results of the insertion/withdrawal data obtained during the 13th, 32nd, and 38th Ag freeze, after heating for 105 h, 580 h, and 1000 h, respectively, are shown in Fig. 1. These and other data demonstrate that approximately 8 cm of immersion are required in Ag cell Ag-65-2 to overcome thermal conduction effects. This is similar to the results reported in Ref. 2. The constancy of the immersion/withdrawal data for greater immersion depths is a measure of the thermoelectric homogeneity of the thermocouple. This thermocouple did not receive a 450 °C or higher temperature anneal during the course of this experiment, so perhaps the slight decrease in values at the greater immersion depths indicates some inhomogeneity due to either quenched-in lattice site vacancies or mechanical stresses or both. These inhomogeneities could possibly have been removed by suitable annealing. The lower *emf* values apparent on withdrawal during the 13th freeze are typical for all freezes in which a conventional measuring junction was used. They are caused by inhomogeneities in the thermocouple wires due to mechanical stresses as described in Ref. 2.

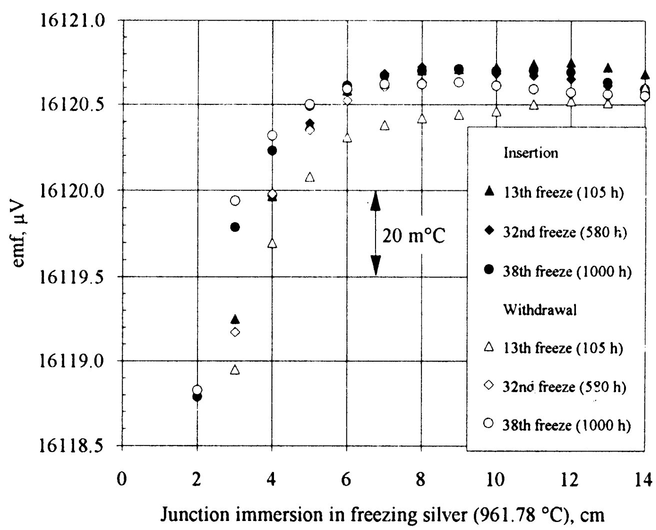

Figure 1. Values of *emf* measured for thermocouple 88-3 on insertion into and withdrawal from the silver freezing-point cell during freezes taken after heating the thermocouple for the indicated times at 961 °C to 965 °C.

The stability data obtained with this thermocouple over the 1000 h of heat treatment at the temperatures indicated above are shown in Fig. 2. As shown in Fig. 2, the equivalent temperature changes of the thermocouple at the freezing point of silver do not exceed ± 16 m°C.

The immersion/withdrawal data for thermocouples 88-4, 88-5, 89-13, and 89-14 in the Al freezing-point cell are shown in Fig. 3 and those for thermocouples 88-2 and 89-12 are shown in Fig. 4. These figures show the data obtained in all Al freezes before and after each of the four comparator runs. It is evident from these figures that the most homogeneous

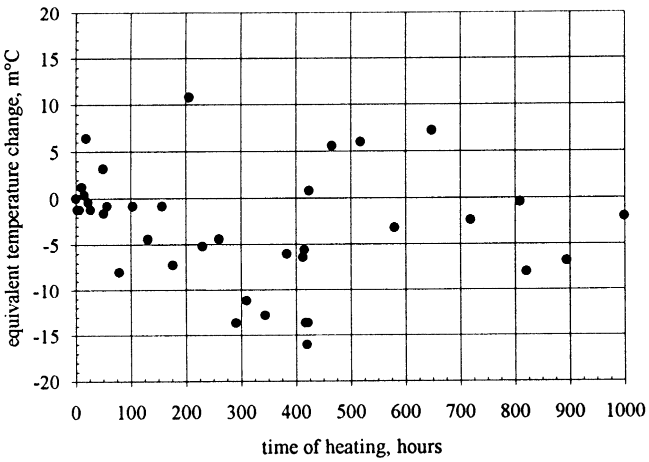

Figure 2. Equivalent temperature change in thermocouple 88-3 at the silver freezing-point (961.78 °C) as a function of time of heating at 961 °C to 965 °C.

thermocouples are 88-4, 88-5 and 89-14. The mean values of the *emf* obtained at full immersion (17.4 cm) from the six Al freezes for thermocouples 88-4 and 88-5 were identical to within the equivalent of 1 m°C. The standard deviations (1 σ) of the data from the six freezes were the equivalent of 2.0 m°C for 88-4 and 1.7 m°C for 88-5. These standard deviations are typical of all of the thermocouples. The standard deviations show more variation at the Ag freezing point, being 2.8 m°C for 88-4 and 2.5 m°C for 88-5. Still, the means for the six Ag freezes were identical to within 1 m°C. These values also are typical of all thermocouples except 88-2, which had a standard deviation for five freezes of 4.2 m°C. The higher *emf* values of thermocouples designated by the prefix 88- are indicative of materials having a higher-purity than those designated by the prefix 89- (see Ref. 2).

During the four comparator runs, the thermocouples experienced approximately 1500 h of heating at temperatures in the range 540 °C to 1000 °C, with about 280 h at temperatures above 900 °C. The reproducibility and homogeneity of these thermocouples after such extensive heating were extraordinary. When compared with results obtained on HTSPRTs (9), the results obtained with the most homogeneous Au/Pt thermocouples demonstrate that they were more stable than HTSPRTs above the Ag freezing-point temperature (961.78 °C).

Based on the thermoelectric quality of thermocouples 88-4 and 88-5, and the close agreement of their *emf*-t_{90} data, these two thermocouples

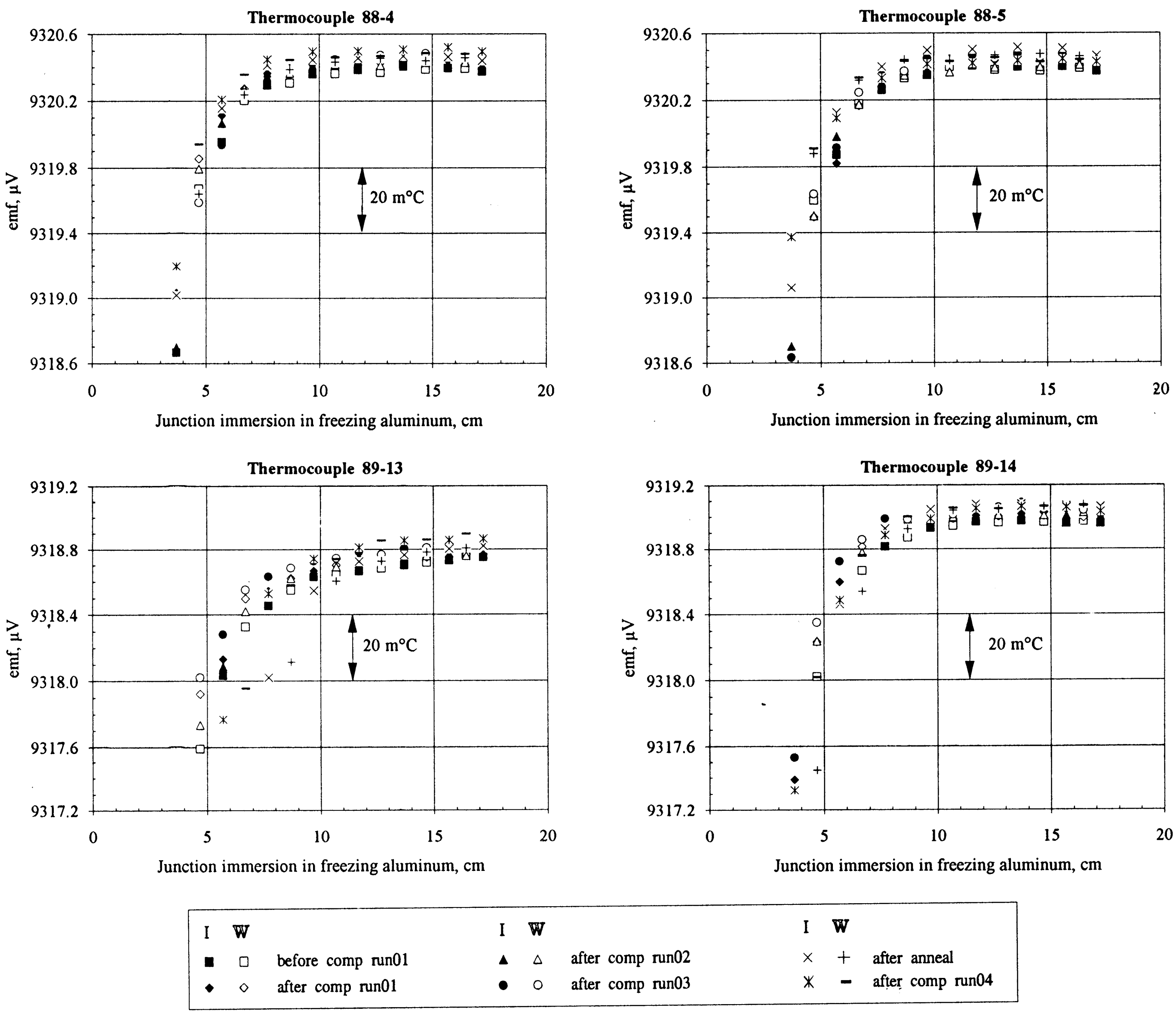

Figure 3. Values of *emf* measured for thermocouples 88-4, 88-5, 89-13, and 89-14 on insertion (I) into and withdrawal (W) from the aluminum freezing-point cell (660.323 °C) during freezes taken before and after each of the four comparator (comp) runs. See text for anneal of thermocouples before comp run04.

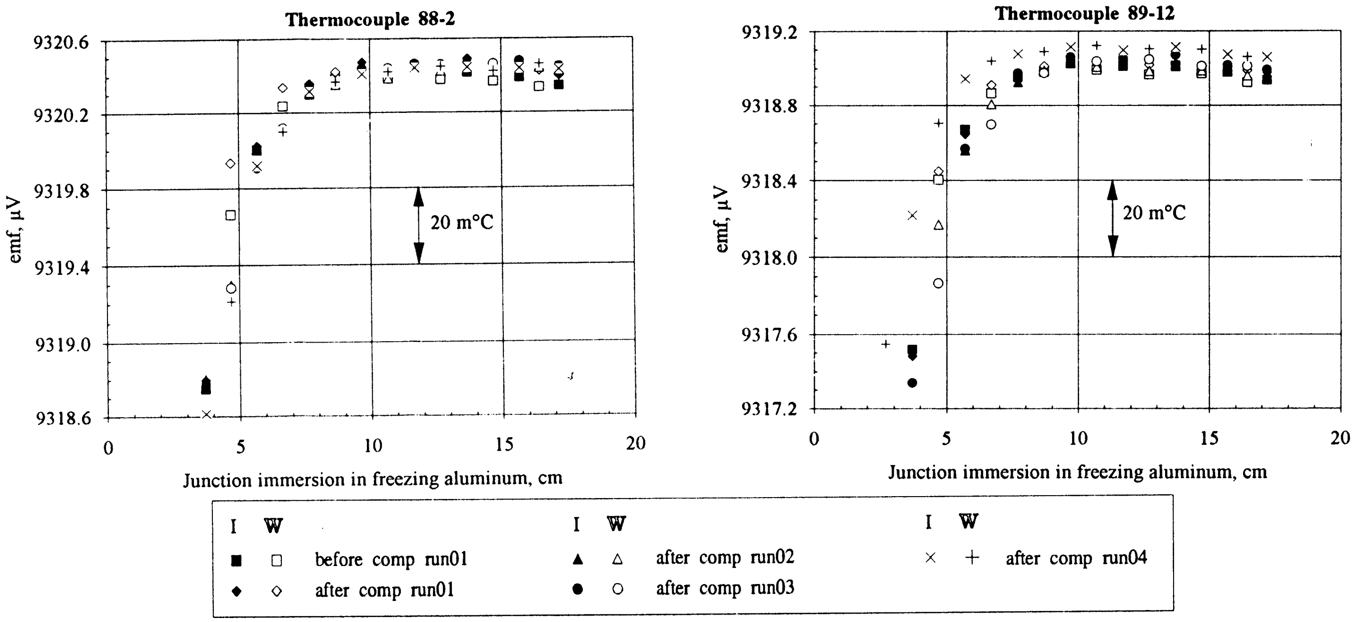

Figure 4. Values of *emf* measured for thermocouples 88-2 and 89-12 on insertion (I) into and withdrawal (W) from the aluminum freezing-point cell (660.323 °C) during freezes taken before and after each of the four comparator (comp) runs.

were selected as the basis for the reference function. The data obtained for these two thermocouples in the liquid baths, in the fixed-point cells, in the second and third comparator runs for temperatures below 850 °C, and in the fourth comparator run were fitted with a 9th degree polynomial, $p(t_{90})$, by the method of least squares. The residual standard deviation was 0.050 µV with 995 degrees of freedom. The *emf* residuals from the fitting are shown in Fig. 5. The data shown in Fig. 5 were reduced by computing the mean of the four replicated sets of data obtained during each run at each temperature for each thermocouple. The results of that reduction are shown in Fig. 6.

The random component of uncertainty for $p(t_{90})$ is calculated using Working-Hotelling confidence bands (10). The upper and lower 95% confidence bands at temperature t_h are $p(t_h) \pm v(t_h)$, where

$$v(t_h) = \sqrt{9F_{0.95}(9,995)}s_h \ . \tag{1}$$

The critical value $F_{0.95}(9,995) = 1.89$ is the upper 95 percent point of the F distribution with 9 and 995 degrees of freedom, and s_h is the standard deviation of $p(t_h)$ at temperature t_h. The Working-Hotelling bands are appropriate for unlimited use of the reference function. Representative values are shown in Table I.

Table I. Random uncertainties (µV) for $p(t_{90})$ from 95% Working-Hotelling confidence bands.

t_{90},°C	$p(t_{90})$	$v(t_{90})$
0	0.00	0.00
100	777.90	0.02
200	1845.08	0.02
300	3141.77	0.02
400	4633.43	0.02
500	6300.95	0.02
600	8135.10	0.01
700	10132.25	0.02
800	12290.89	0.02
900	14609.31	0.02
1000	17085.31	0.04

The new reference function for Au/Pt thermocouples is of the form:

$$E = p(t_{90}) = \sum_{i=1}^{9} a_i \, (t_{90})^i, \tag{2}$$

where t_{90} is in degrees Celsius and E is the *emf* in microvolts. The coefficients of Eq. (2) for the range 0 °C to 1000 °C are given in Table II. Values of E and the first and second derivatives of E with respect to t_{90} computed from Eq. (2) at selected values of t_{90} are given in Table III.

Table II. Coefficients for Au/Pt thermocouple reference function for the range 0 °C to 1000 °C.

a_1	6.03619861	a_5	$-4.24206193 \times 10^{-11}$
a_2	$1.93672974 \times 10^{-2}$	a_6	$4.56927038 \times 10^{-14}$
a_3	$-2.22998614 \times 10^{-5}$	a_7	$-3.39430259 \times 10^{-17}$
a_4	$3.28711859 \times 10^{-8}$	a_8	$1.42981590 \times 10^{-20}$
		a_9	$-2.51672787 \times 10^{-24}$

Table III. Values of E and the first and second derivatives of E with respect to t_{90} computed from equation (2) at selected values of t_{90}.

t_{90}, °C	E, µV	dE/dt_{90}, µV/°C	d^2E/dt_{90}^2, nV/°C^2
0.00	0.00	6.036	38.73
0.01	0.06	6.037	38.73
29.7646	196.26	7.133	35.08
156.5985	1350.94	10.861	24.90
231.928	2236.18	12.599	21.46
419.527	4945.63	16.157	17.27
630.615	8729.30	19.658	16.24
660.323	9320.44	20.139	16.20
961.78	16120.49	24.945	15.65
1000.00	17085.31	25.543	15.64

In Fig. 7, we show the difference between our reference function and that of Gotoh *et al* (4). Their reference function, which fitted their experimental data within ±10 m°C, is represented by an 8th degree polynomial that gives the *emf* as a function of t_{90} from 0 °C to 962 °C. Their reference function is based on slightly less pure materials than ours, as indicated by its lower *emf* values. Figure 7 also shows the experimental data for our thermocouple 89-14 and a 9th degree polynomial that was fitted to the data for 89-14 by the method of least squares. The residual standard deviation was 0.049 µV with 409 degrees of freedom. The reference function of Gotoh *et al.* is in agreement with the function for 89-14 within 22 m°C over the entire range of temperatures. The maximum *emf* difference between the function of Gotoh *et al.* and that for 89-14 occurs at 555 °C. It should be noted that Gotoh *et al.* (4) had no experimental data between 494 °C and 630 °C.

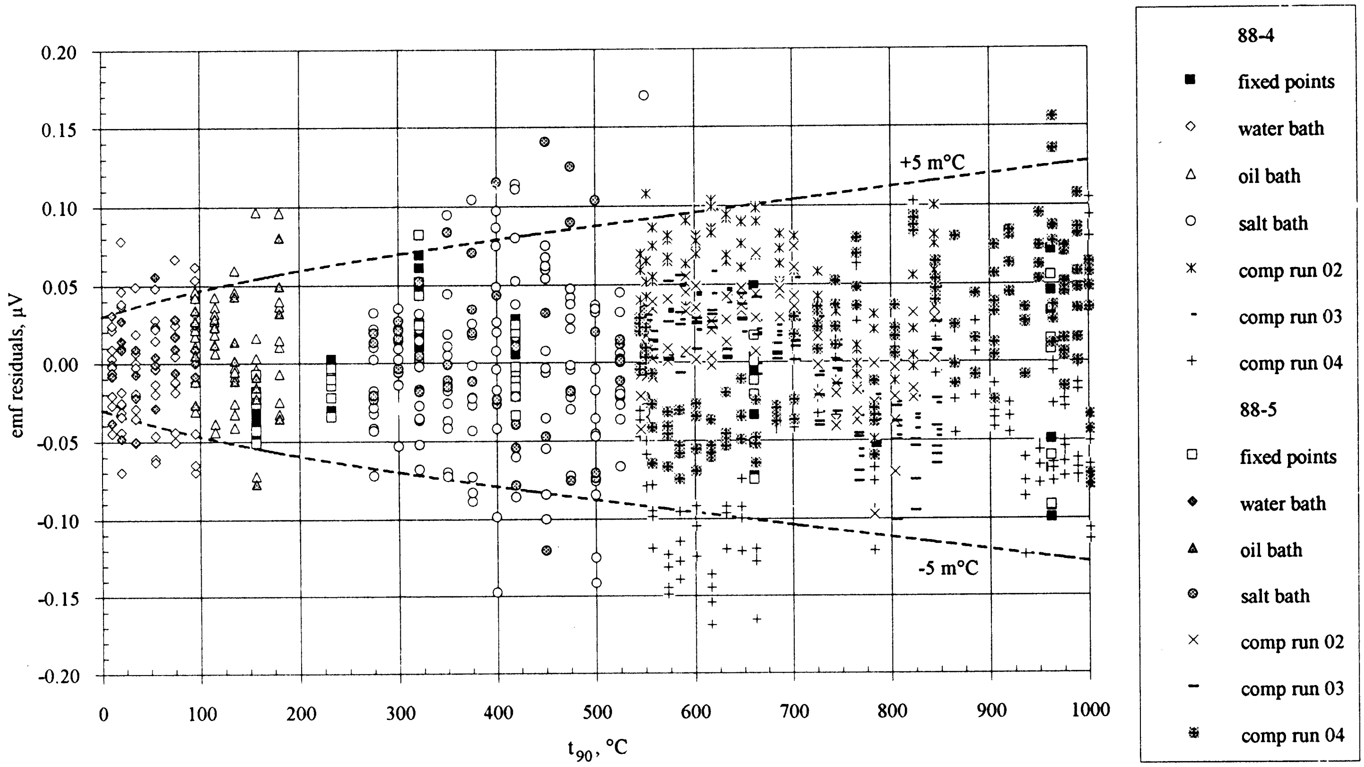

Figure 5. Residuals from a 9th degree polynomial that was fitted to the data of thermocouples 88-4 and 88-5. The dashed lines indicate *emf* residuals equivalent to ±5 m°C.

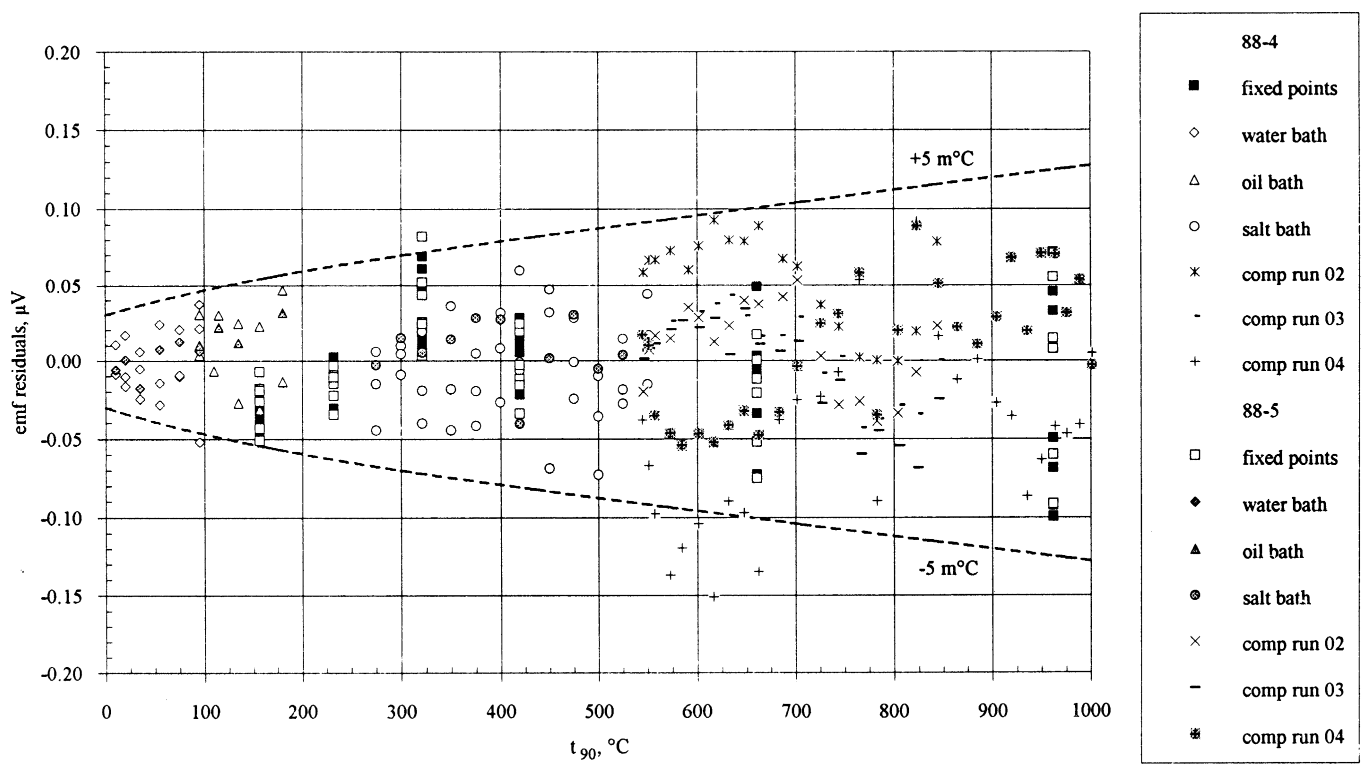

Figure 6. Same as Fig. 5 except that the data of thermocouples 88-4 and 88-5 have been reduced by computing the mean of the four replicated sets of data obtained during each run at each temperature for each thermocouple. The dashed lines indicate *emf* residuals equivalent to ±5 m°C.

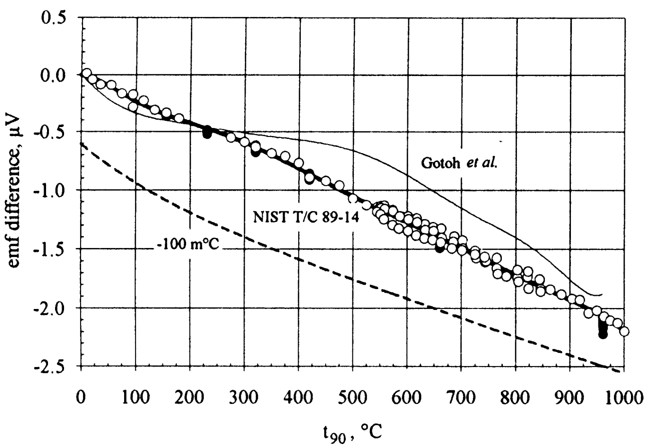

Figure 7. Difference between the reference function for Au/Pt thermocouples given by Gotoh *et al.* (thin line) and the reference function presented in this paper. The difference of the data for NIST thermocouple 89-14 from the reference function is shown also. The solid symbols denote fixed-point data and the open symbols denote comparison data. The thick line represents the 9th degree polynomial fitted to the data. The dashed line indicates an *emf* difference equivalent to −100 m°C.

The deviations of the data for thermocouples 88-2, 89-12, and 89-13 from the new reference function are shown in Fig. 8. Above 200 °C, the data for 89-12 and 89-13 agree closely, but these two thermocouples were not as homogeneous as 89-14 and their *emf* values are slightly lower than those of 89-14 (see Fig. 7).

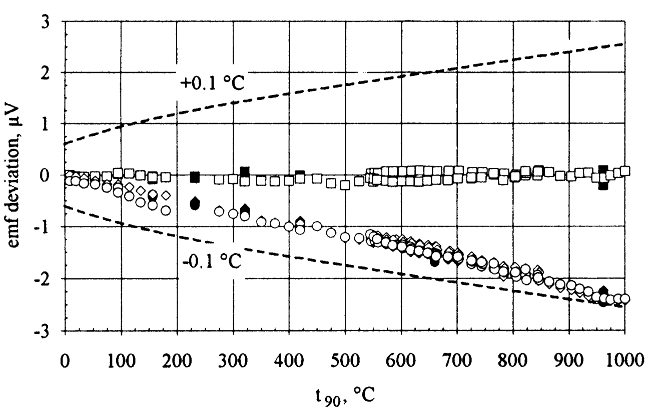

Figure 8. Deviations of the data for thermocouples 88-2 (squares), 89-12 (diamonds), and 89-13 (circles) from the reference function. The dashed lines indicate *emf* deviations equivalent to ±0.1 °C. The solid symbols denote fixed-point data and the open symbols denote comparison data.

Since the reference function given by Eq. (2) is not well suited for calculating values of temperature from values of *emf*, two inverse functions are included here for that purpose. These inverse functions give values of temperature that agree with values obtained from the reference function to at least ±5 m°C, where the *emf* (E) is given in microvolts. Equation (3) gives the form of an inverse function for the Au/Pt thermocouple for the temperature and *emf* ranges, 0 °C to 209 °C and 0 μV to 1953 μV. The coefficients for Eq. (3) are given in Table IV.

$$t_{90} = \sum_{i=1}^{8} b_i (E)^i \qquad (3)$$

Table IV. Coefficients of the inverse function, Eq. (3), for the Au/Pt thermocouple for the range 0 °C to 209 °C.

b_1	1.6543903×10^{-1}	b_5	$4.8495536 \times 10^{-14}$
b_2	$-8.4098835 \times 10^{-5}$	b_6	$-2.0138760 \times 10^{-17}$
b_3	8.4166132×10^{-8}	b_7	$4.7475626 \times 10^{-21}$
b_4	$-7.5174691 \times 10^{-11}$	b_8	$-4.7973082 \times 10^{-25}$

Equation (4) gives the form of an inverse function for the Au/Pt thermocouple for the temperature and *emf* ranges, 209 °C to 1000 °C and 1953 μV to 17085 μV. The coefficients for Eq. (4) are given in Table V.

$$t_{90} = \sum_{i=0}^{11} b_i \left((E - 9645)/7620\right)^i \qquad (4)$$

Table V. Coefficients of the inverse function, Eq. (4), for the Au/Pt thermocouple for the range 209 °C to 1000 °C.

b_0	6.763360×10^{2}	b_6	-3.385575
b_1	3.735504×10^{2}	b_7	3.853735
b_2	-5.537363×10^{1}	b_8	1.178891
b_3	1.701900×10^{1}	b_9	-2.702558
b_4	-6.098761	b_{10}	-1.686158
b_5	2.457162	b_{11}	1.876968

REFERENCES

[a] This work was funded in part by an Interagency Agreement with NASA - Langley Research Center, PO Number 94846C.

[b] Guest Researcher, Shanghai Institute of Metrological Technology, P.R.C.

[c] Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

1. W.F. Roeser and H.T. Wensel, in *Temperature, Its Measurement and Control in Science and Industry*, Vol. 1, (Reinhold Publishing Co., New York, 1941), Appendix, Table 12, p. 1309.
2. E.H. McLaren and E.G. Murdock, The Pt/Au Thermocouple, Part I: Essential Performance, Part II: Preparatory Heat Treatment, Wire Comparisons and Provisional Scale, National Research Council of Canada Publication NRCC/27703, Ottawa, Canada, 1987.
3. H. Preston-Thomas, The International Temperature Scale of 1990, Metrologia *27*, 3-10 (1990), ibid. p. 107.
4. M. Gotoh, K.D. Hill and E.G. Murdock, A gold/platinum thermocouple reference table, Rev. Sci. Instrum. *62*, 2778-2791 (1991).
5. G.W. Burns and M.G. Scroger, The Calibration of Thermocouples and Thermocouple Materials, Natl. Inst. Stand. Technol. Spec. Publ. 250-35, (U.S. Government Printing Office, Washington, DC 1989).
6. B.W. Mangum, Platinum Resistance Thermometer Calibrations, Natl. Inst. Stand. Technol. Spec. Publ. 250-22, (U.S. Government Printing Office, Washington, DC 1987).
7. G.F. Strouse, NIST implementation and realization of the ITS-90 over the range 83 K to 1235 K; reproducibility, stability, and uncertainties, *Temperature: Its Measurement and Control in Science and Industry*, Edited by J. F. Schooley, Vol. 6, (American Institute of Physics, New York, 1992).
8. G. W. Burns, G. F. Strouse, B. W. Mangum, M. C. Croarkin, W. F. Guthrie, P. Marcarino, M. Battuello, H. K. Lee, J. C. Kim, K. S. Gam, C. Rhee, M. Chattle, M. Arai and H. Sakurai, A. I. Pokhodun, N. P. Moiseeva, S. A. Perevalova, M. J. de Groot, J. Zhang, K. Fan, and S. Wu, New reference function for platinum-10% rhodium versus platinum (type S) thermocouples based on the ITS-90, *Temperature: Its Measurement and Control in Science and Industry*, Edited by J. F. Schooley, Vol. 6, (American Institute of Physics, New York, 1992).
9. G.F. Strouse, B.W. Mangum, A.I. Pokhodun, and N.P. Moiseeva, Investigation of high-temperature platinum resistance thermometers at temperatures up to 962 °C, and in some cases, 1064 °C, *Temperature: Its Measurement and Control in Science and Industry*, Edited by J. F. Schooley, Vol. 6, (American Institute of Physics, New York, 1992).
10. J. Neter, W. Wasserman, and M. Kutner, *Applied Linear Regression Models*, (Richhard D. Irwin, Inc., Homewood, Illinois, 1983), p. 244.